InSAR Scattering Phase Centre of Antarctic Snow
An Experimental Study

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- Δh TDM –Cryosat for Ice and Firn Areas
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- Relations between Penetration Bias and Interferometric Signals

Satellite Data Base for the Study:

- **TanDEM-X**: Single-pass InSAR (9.6 GHz)

  CoSSc data and DEMs 2013/14 & Dec 2016 to Feb 2017

  TDM Global DEM (based on multiple acquisitions 2013/2014)
- **ICESat**: Multiple tracks, 2003 to 2009
- **CryoSat:** (13.8 GHz) L-2 surface elevation (SARIn), 2010-2014

Study Approach

Criteria for Selection of the Study Area

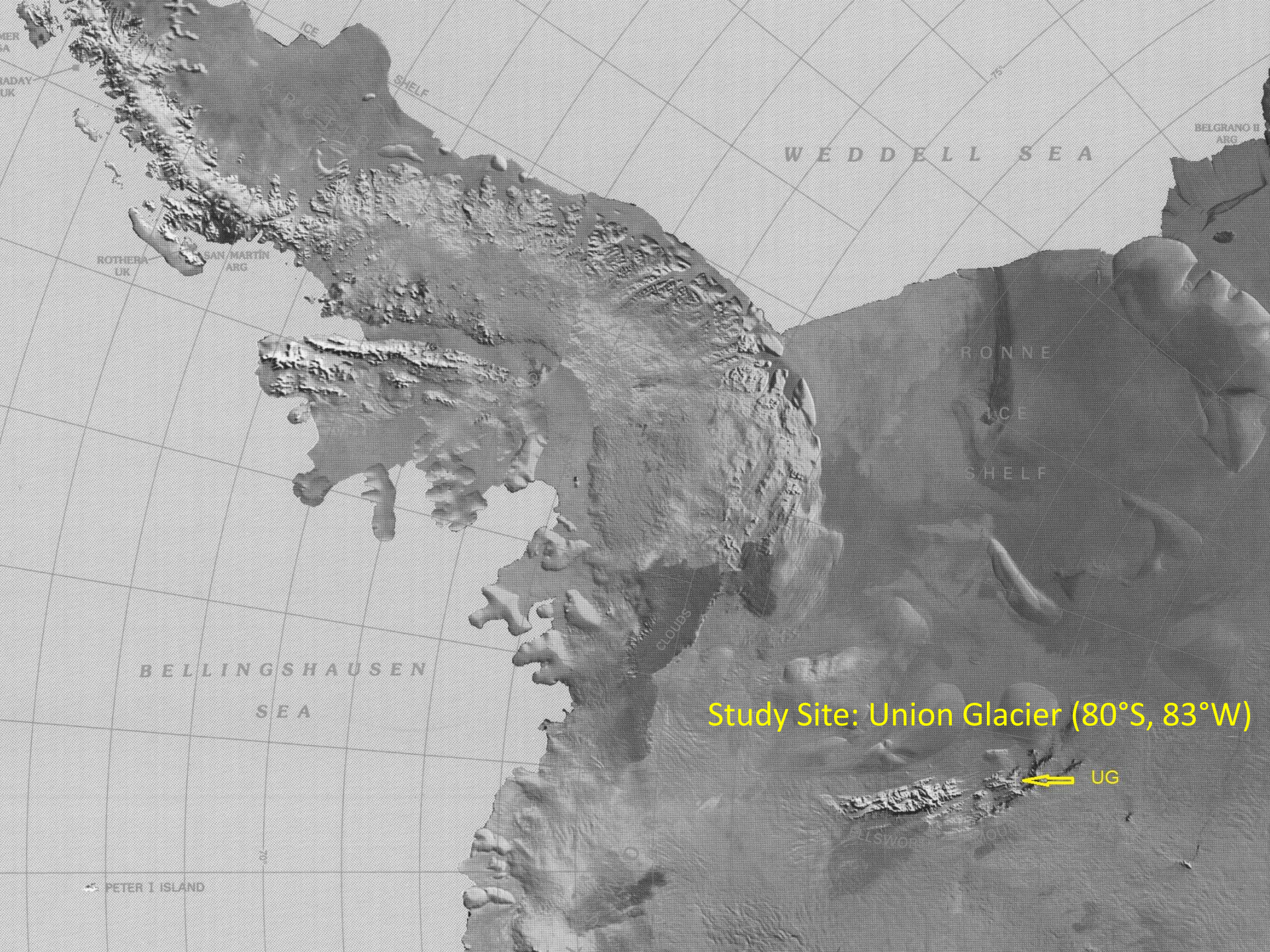
- Reference surface defined by precise laser altimetry data → ICESat
- Study area with stationary surfaces (dh/dt ≈ 0 since 2003)
- Should include different snow morphologies and bare ice surfaces
- Availability of logistic support

Field Measurements (December 2016)

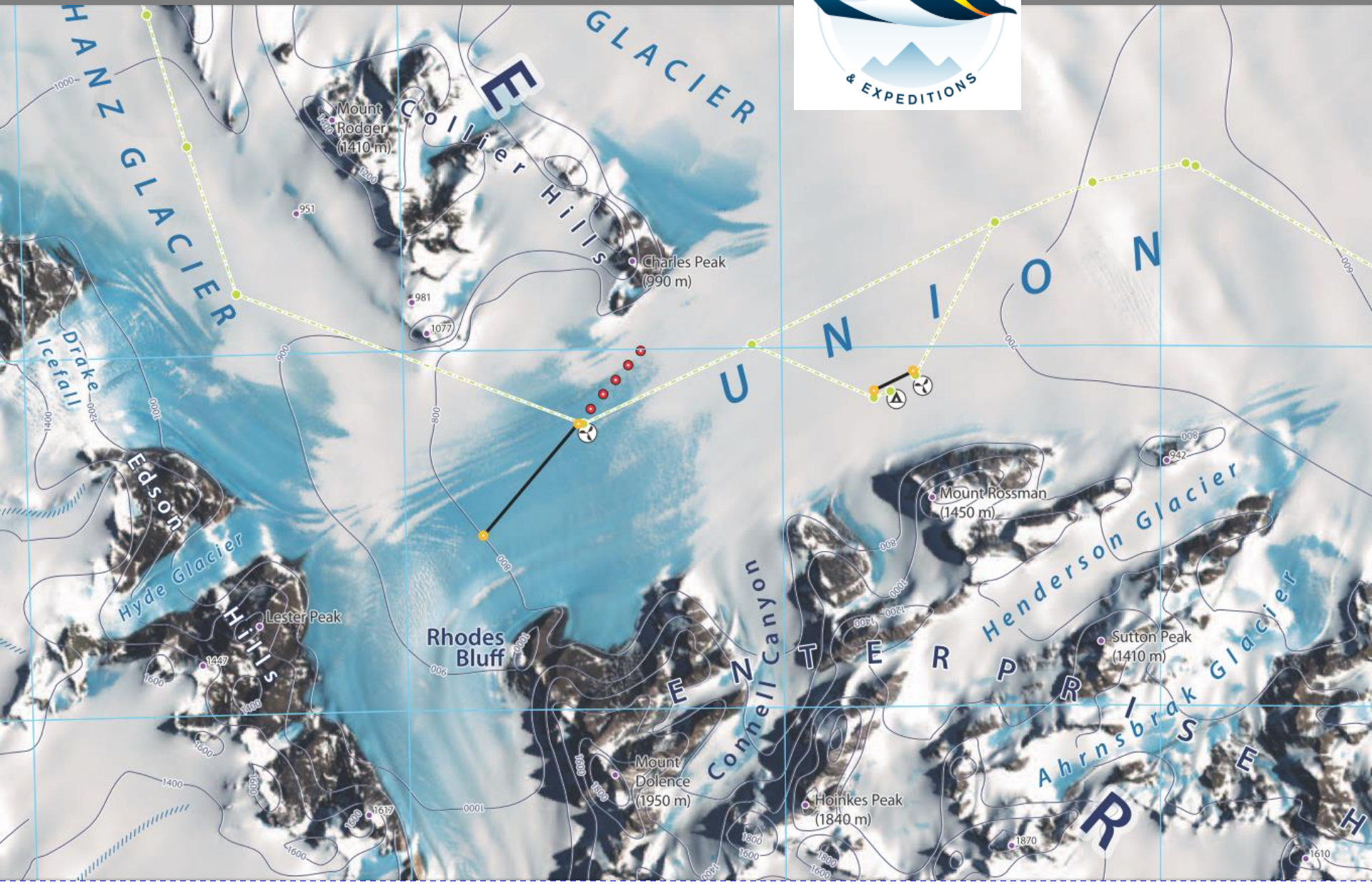
- Snow and firn stratigraphy and structure in snow pits (sites with different accumulation rates and wind exposure)

Data Analysis

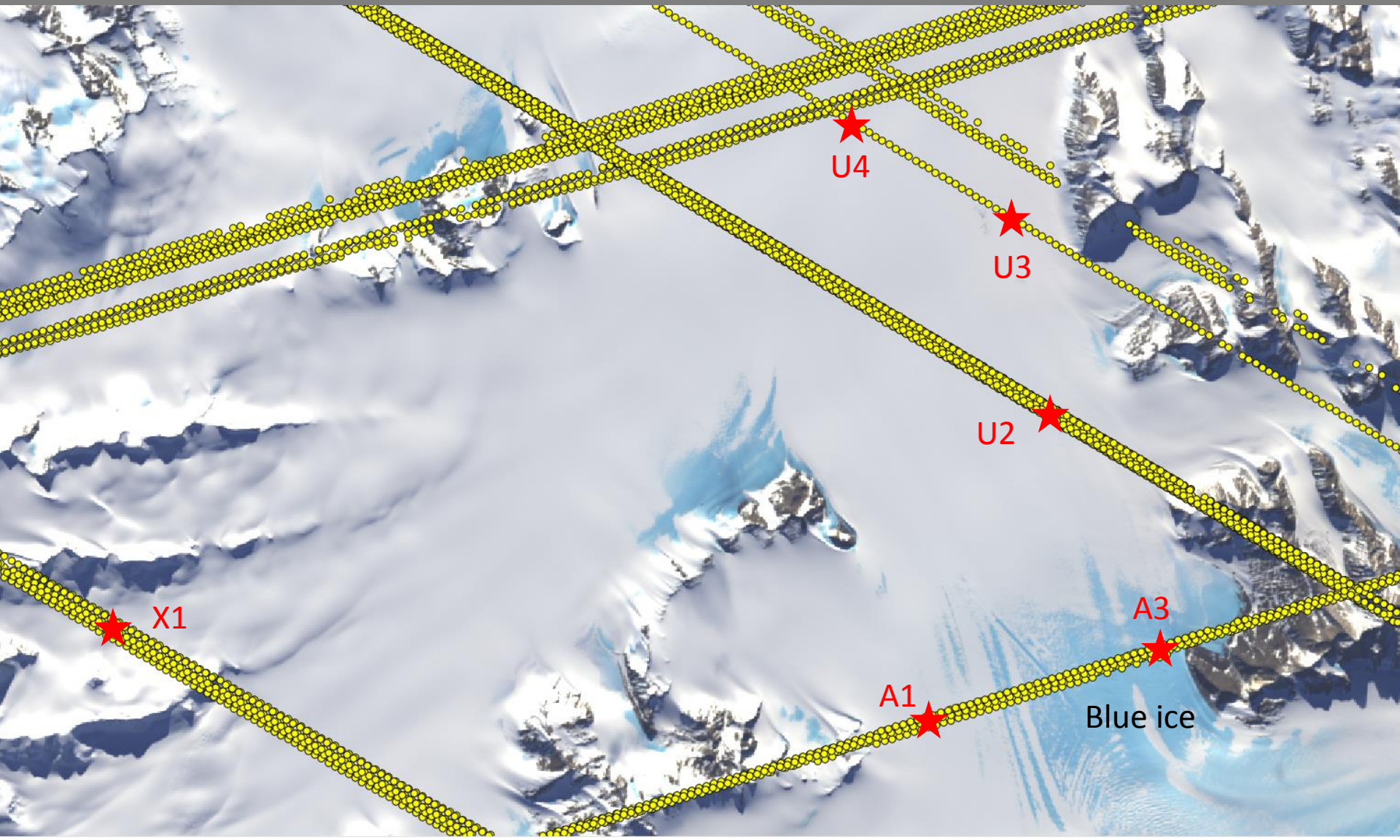
- Derive elevation difference $\Delta h = h_{ICESat} - h_{TDM}$ along ICESat tracks
- Use data over blue ice area as reference for vertical co-registration of the ICESat (reference surface) and TDM_{glob} DEMs
- For the blue ice area (dominated surface scattering) zero penetration for TDM is assumed (penetration bias $\Delta h_p = 0$)


WEDDELL SEA
RONNE
ICE
SHELF
BELLINGSHAUSEN
SEA
CLOUDS
ROTHERA
UK
BELGRANO II
ARG
PETER I ISLAND
Study Site: Union Glacier (80°S, 83°W)
UG

ALE Base Camp and Runways

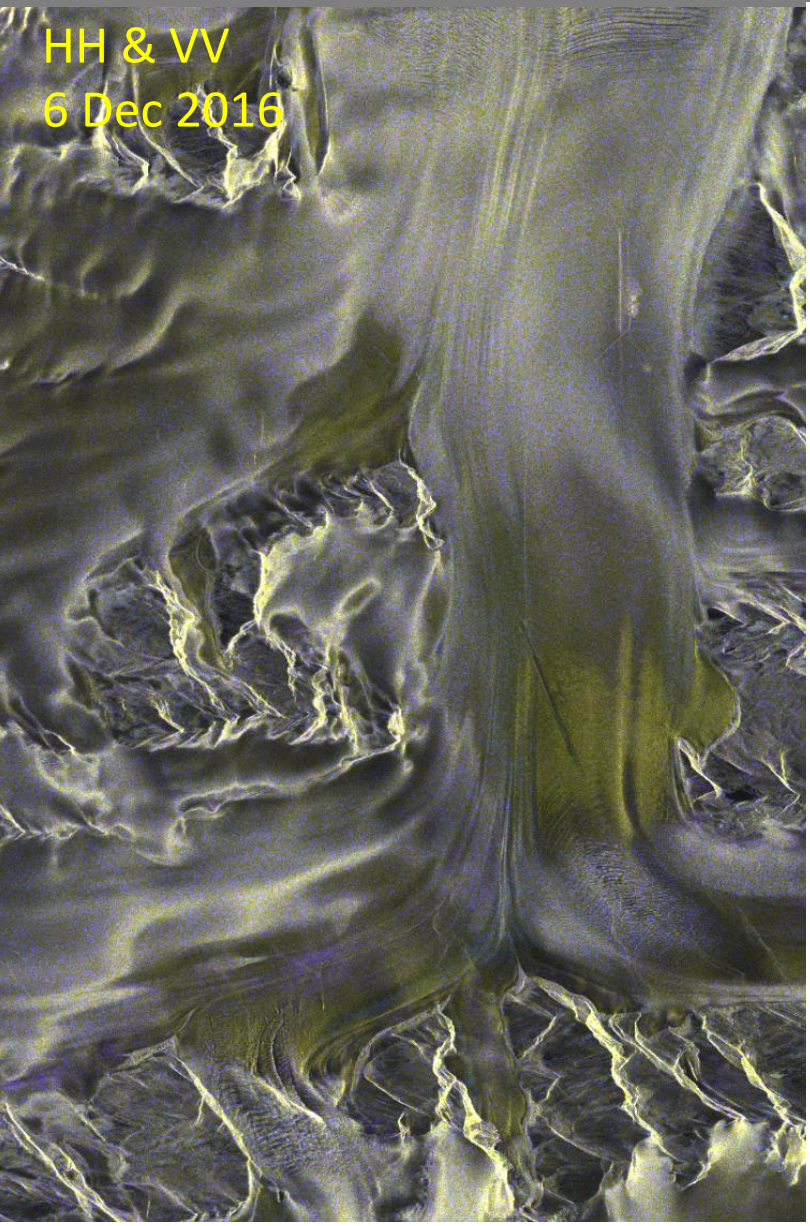


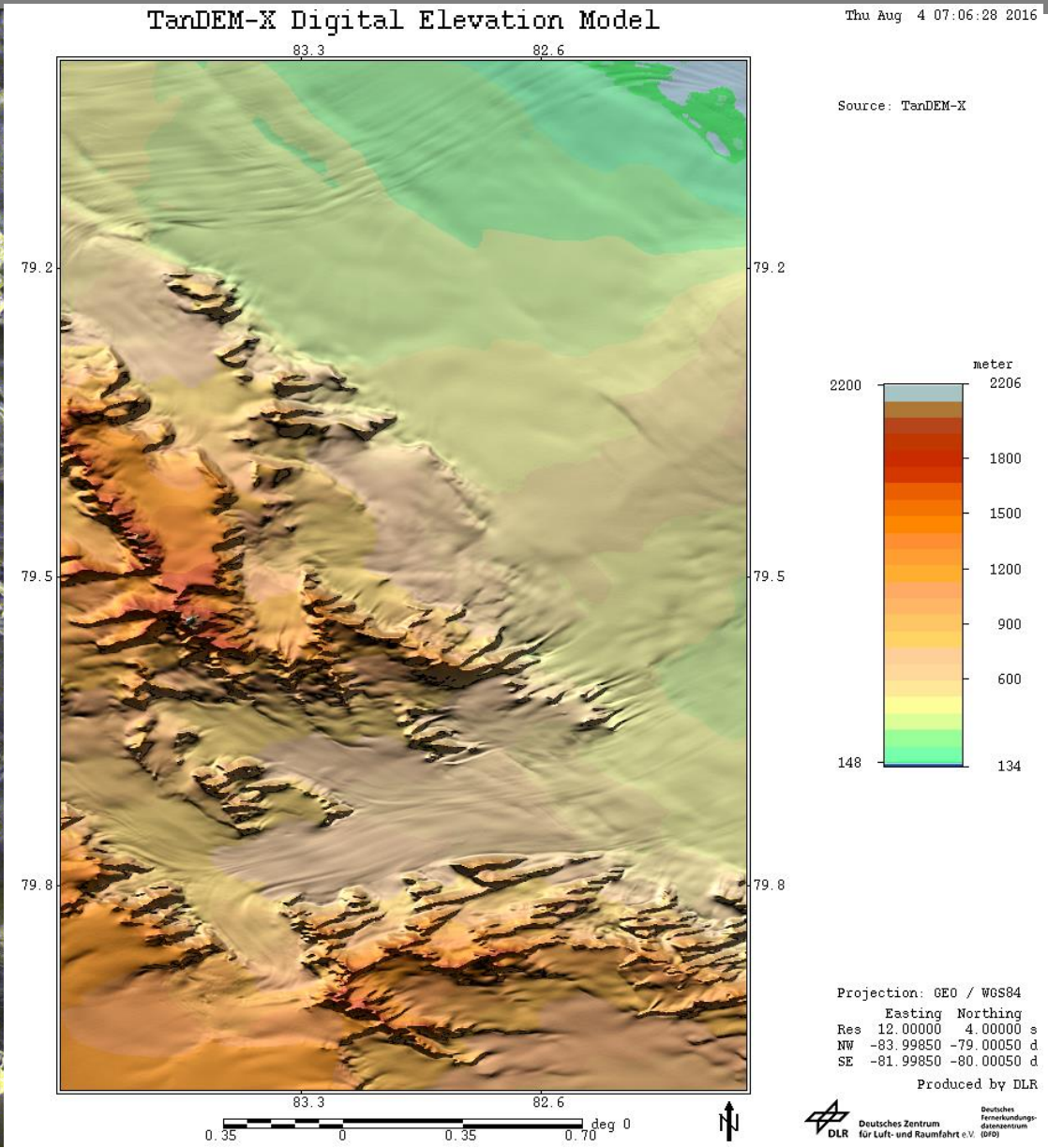
ICESat Tracks and Field Sites



Landsat-8 6 Dec. 2016

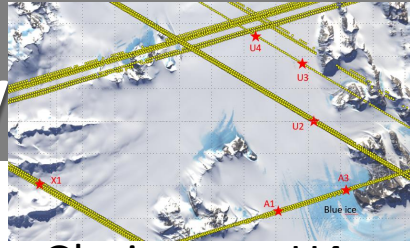
TanDEM-X Amplitude Image and Global DEM



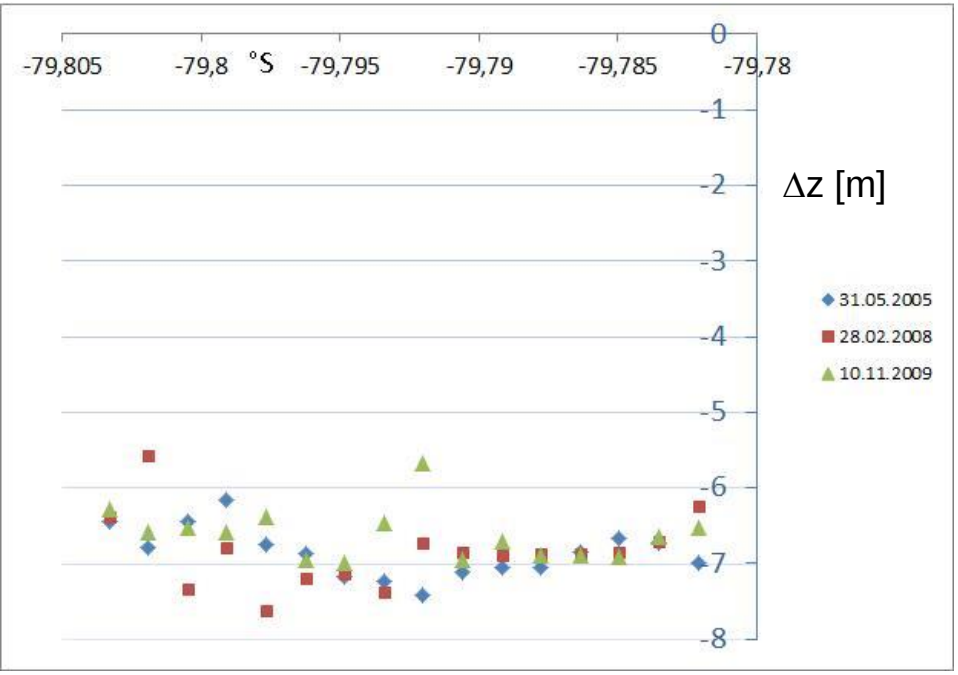


Reference Surface for $\Delta h_p = 0$: Blue Ice

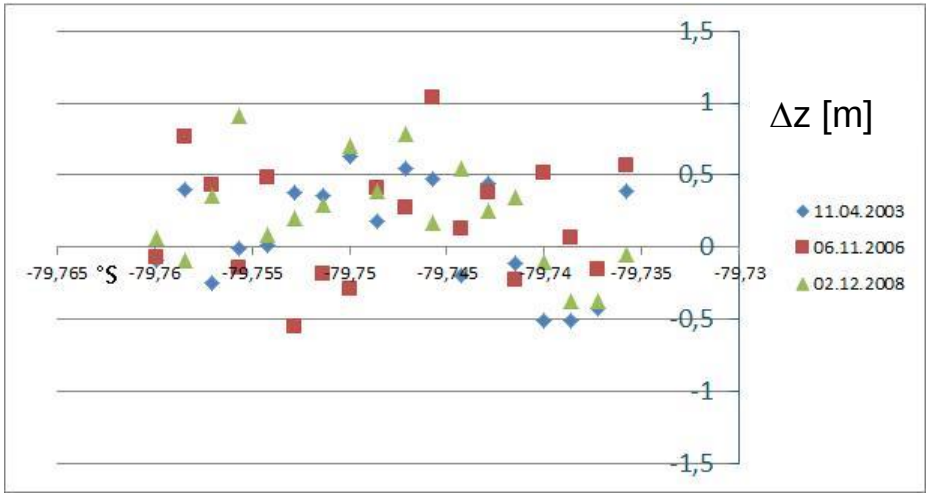
Comparison ICESat – TanDEM-X / **Temporal Stability**



Δz (ICESat-TDM_{global})
Tracks across blue ice field



Δz (ICESat-TDM_{global})
ICESat tracks across Union Glacier near U4
Firn area



Δz (ICESat-TDM_{global}) for repeat track

04-2003	05-2004	09-2005	11-2006	12-2006	03-2007	12-2008
0.10m	0.13	-0.02	0.19	0.09	0.01	0.23

$\Delta Z0$ (ICESat-TDM_{global}) blue ice
2005 -6.86 m
2008 -6.84 m
2009 -6.62 m

Blue ice: no radar signal penetration, $\Delta h_p = 0$

Mean offset ICESat - TDM_{global} $\Delta Z0 = -6.8$ m

U4: Mean $\Delta z = 0.10$ m (± 0.12 m)
$\Delta h_p = \Delta Z0 - \Delta z = -6.9$ m
Local bias due to radar penetration

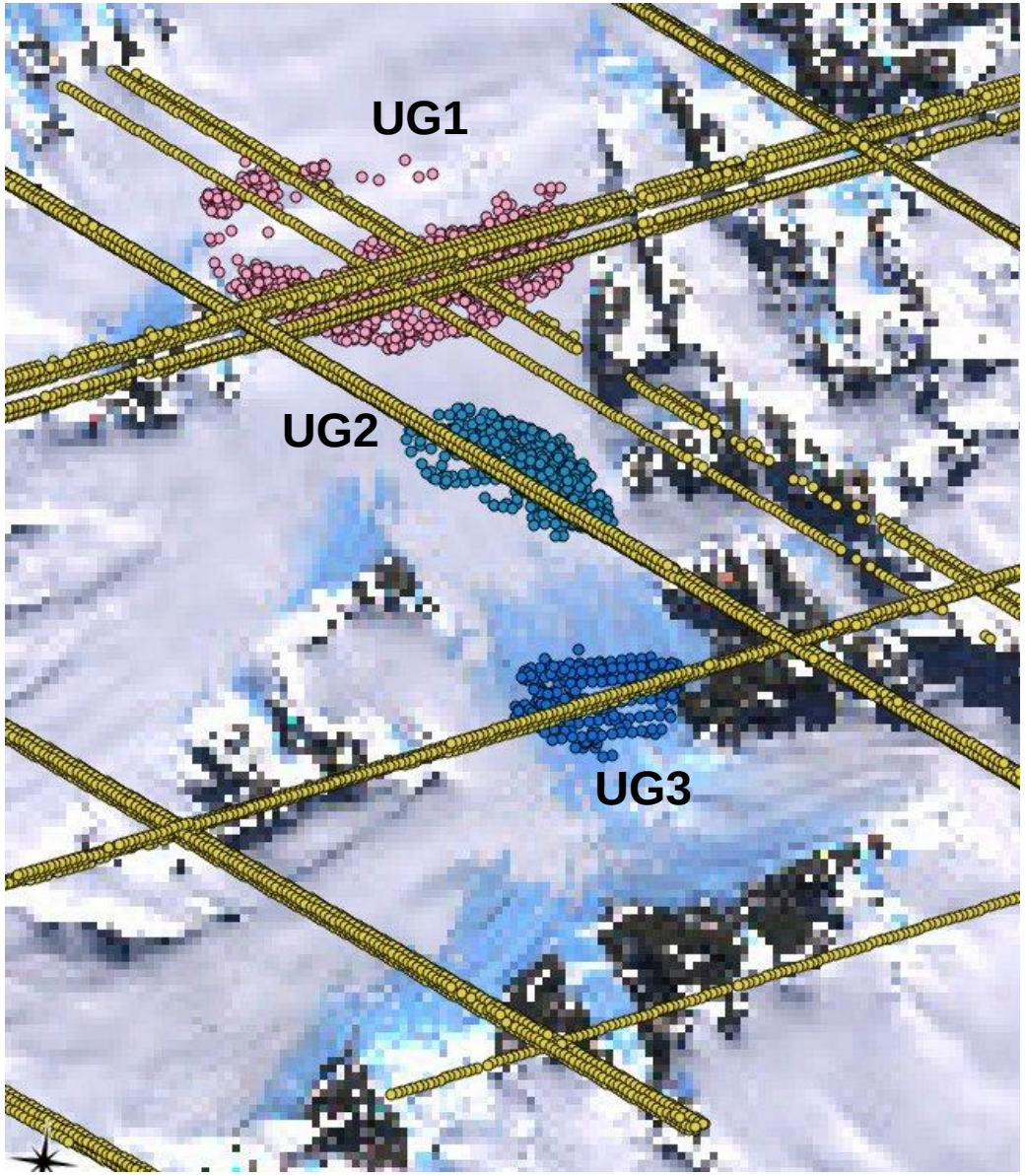
Comparison TDM Global DEM - CryoSat

Areas for Comparison:

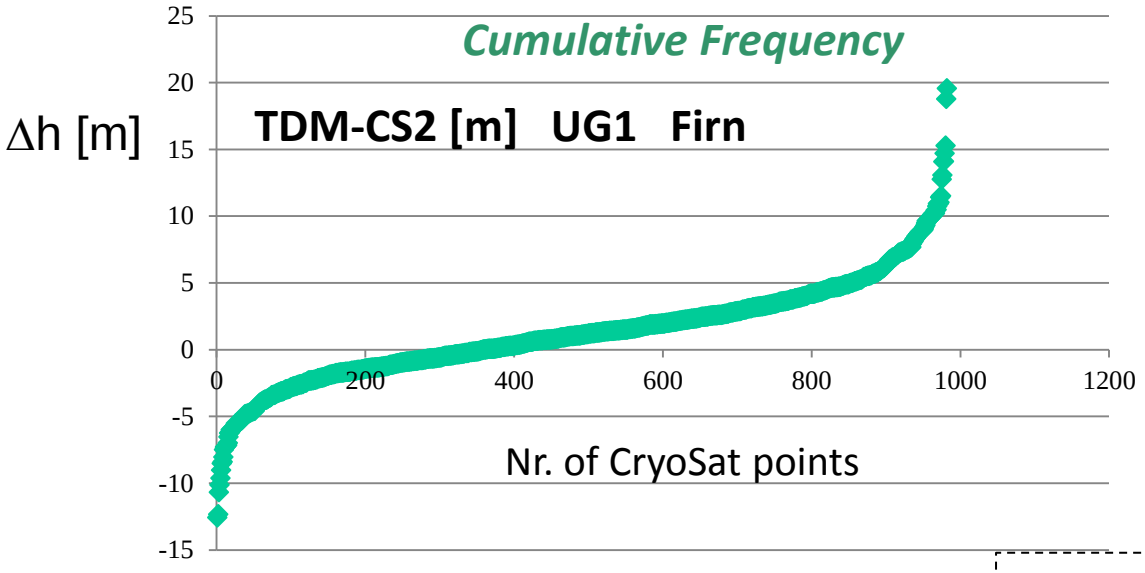
UG1: accumulation rate
$b_a \approx 200$ mm/yr

UG2: accumulation rate
$b_a \approx 150$ mm/yr

UG3: Blue ice



Comparison TDM Global DEM - CryoSat



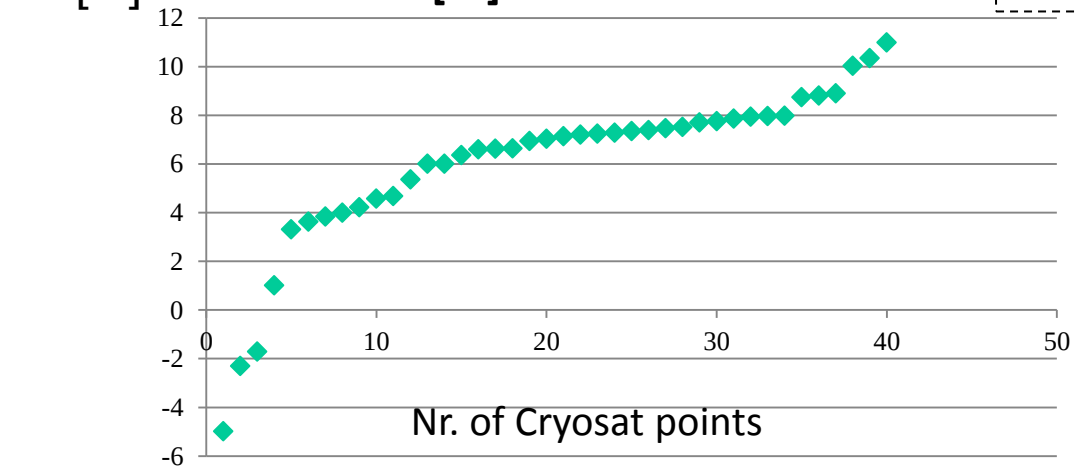
UG1: Mean TDM – CS2: 1.29m

With TDM ΔZ0 = -6.8 m:

Δh(TDM – CS2) = -5.51 m

Difference TDM / CS2 due to penetration $\Delta h_p \approx$ -5 m.

All CS2 points with $|\Delta h| > 20$ m excluded.

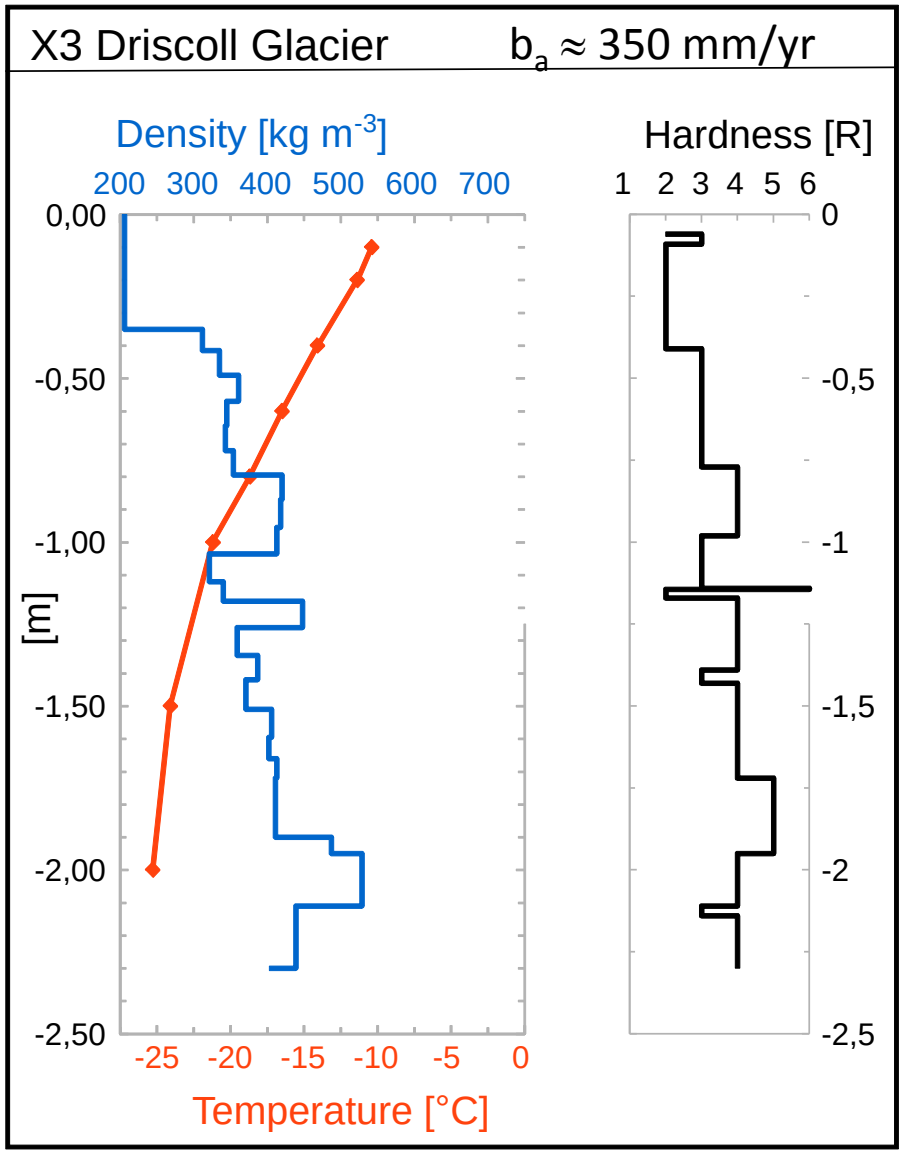


Mean Δh(TDM – CS2): 6.03 m

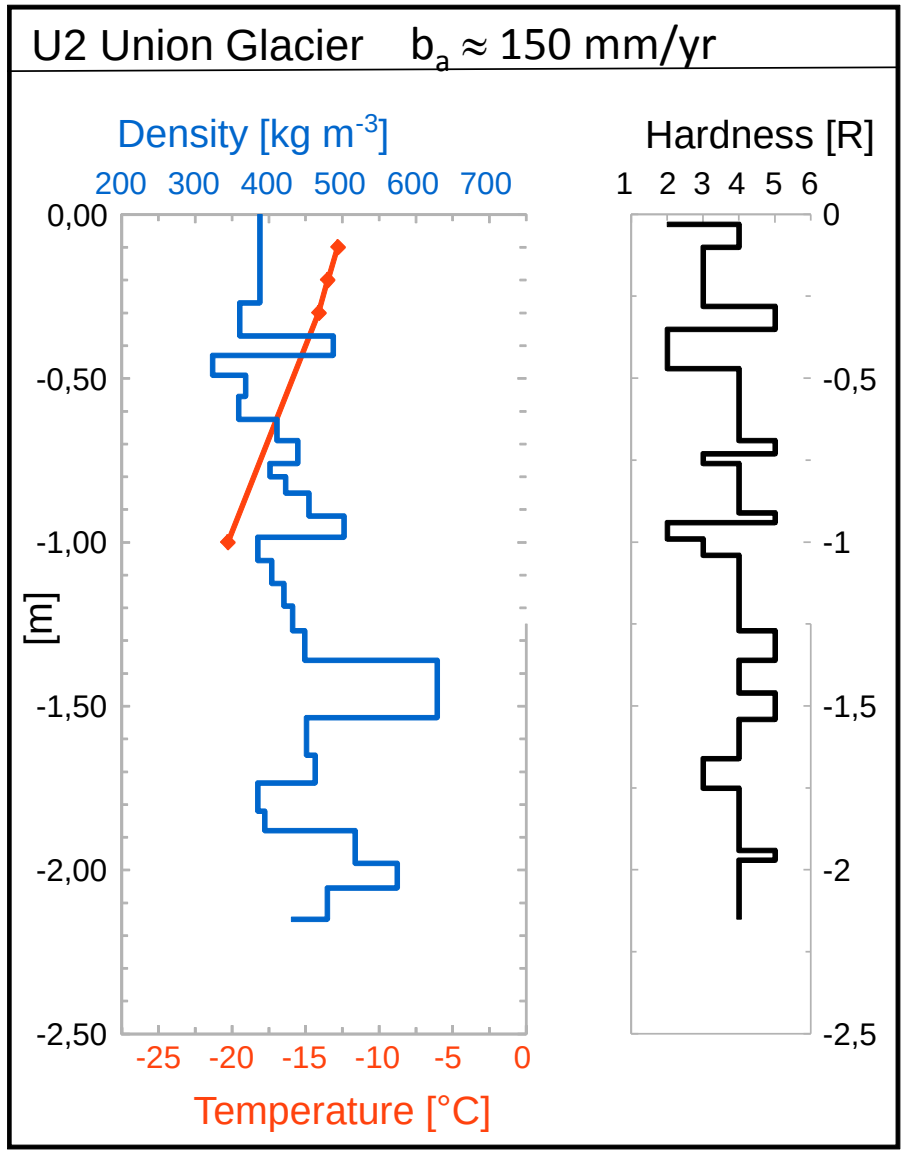
With TDM ΔZ0 = -6.8 m:

Δh(TDM – CS2) = -0.77 m

Differences in Stratigraphy and Penetration



Δh_p = -6.5 m, site on firn plateau

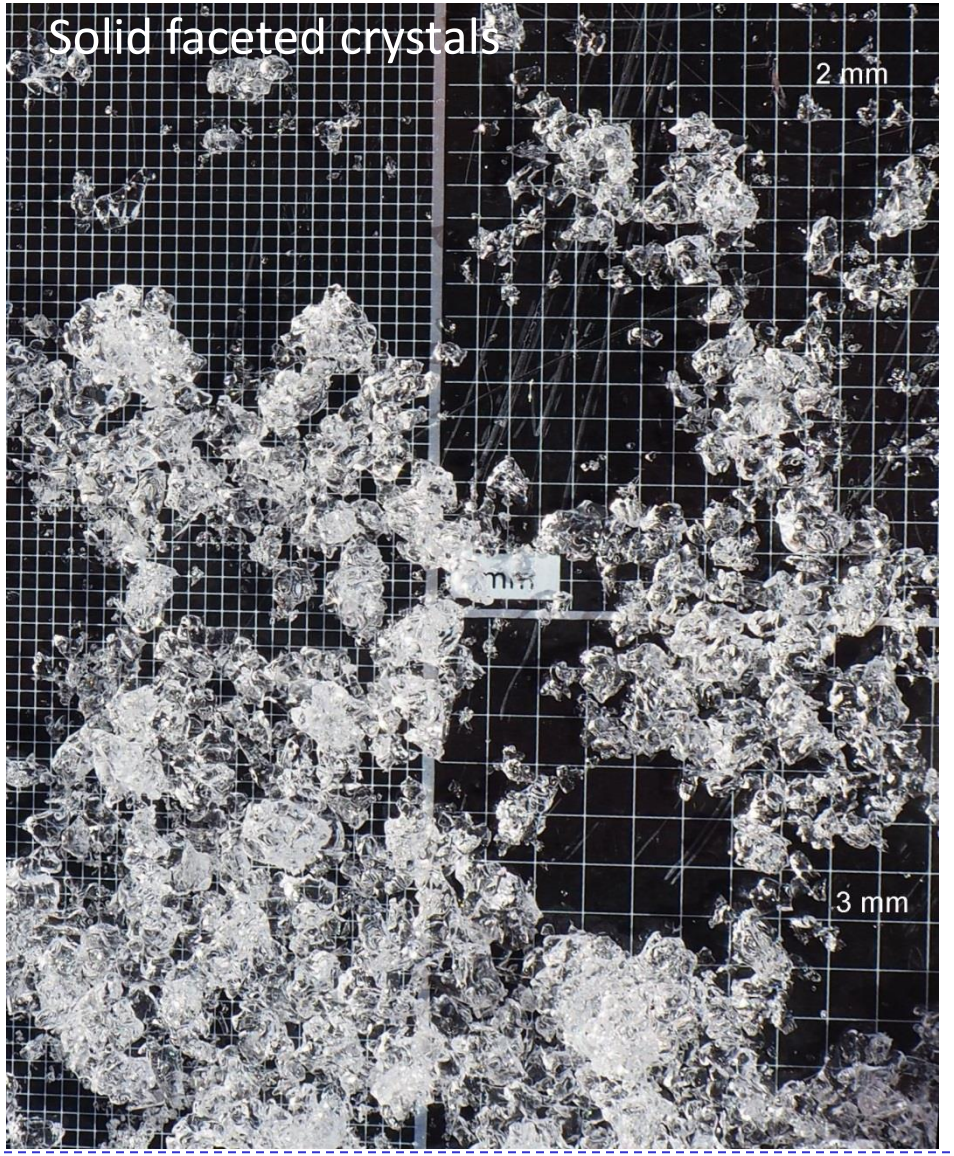


Δh_p = -4.9 m, firn area on main glacier

Snow Morphology

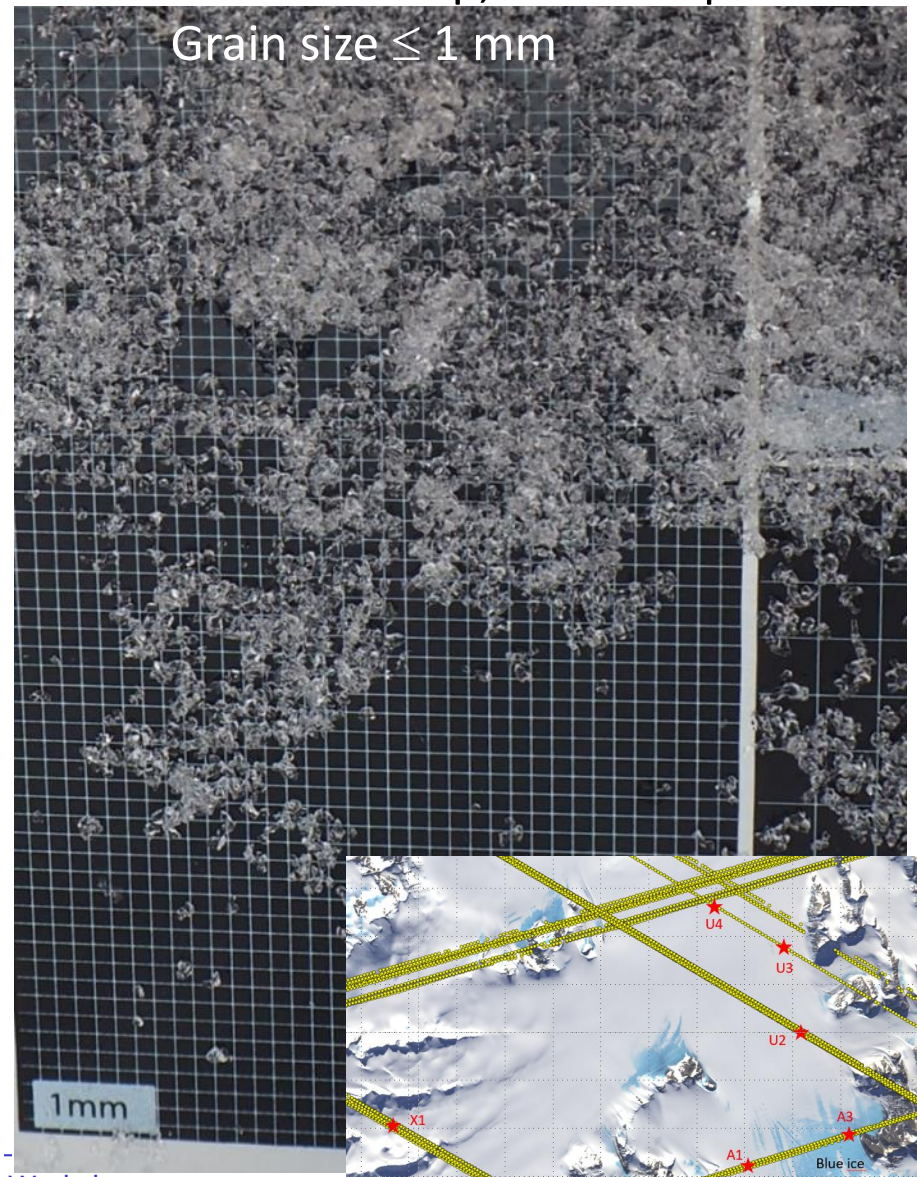
A1 (heavy wind exposure)

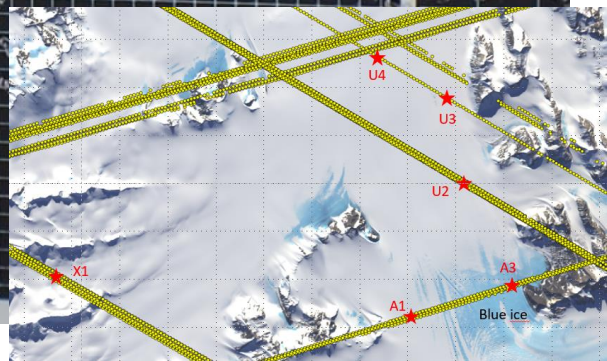
Solid faceted crystals



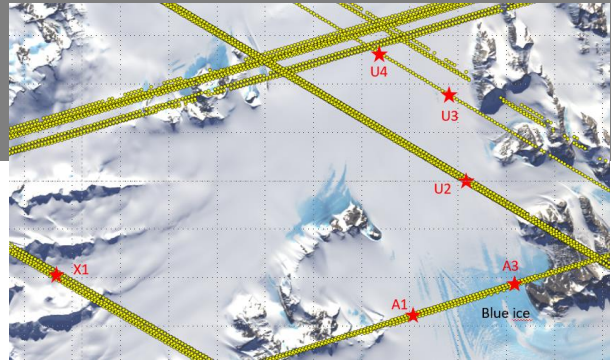
U3 near Camp, 50 cm depth

Grain size ≤ 1 mm





Penetration Bias vs. Coherence and Backscatter

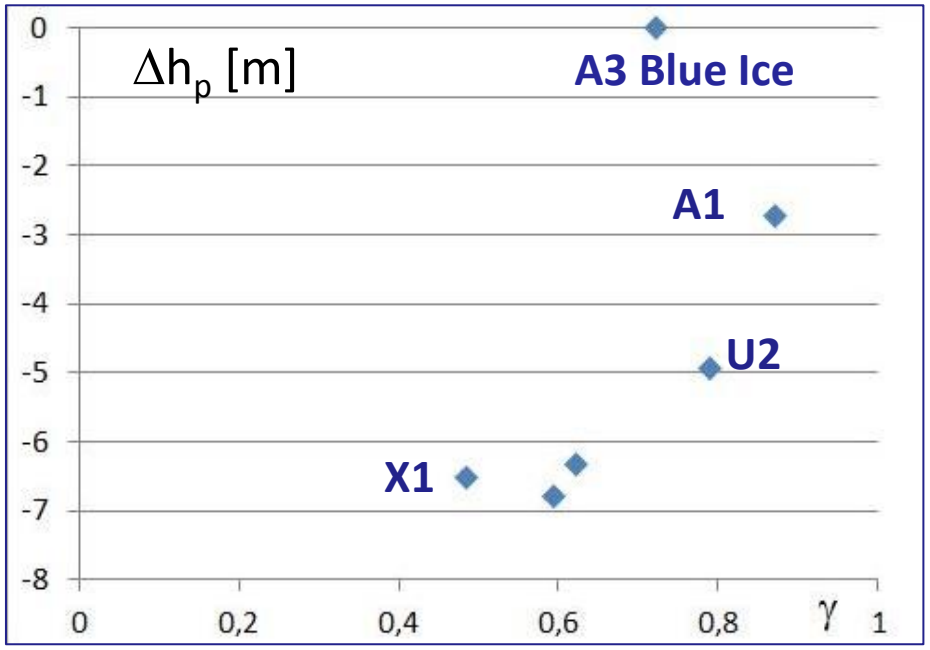


Δh_p - penetration bias for TDM (blue ice zero ref.)

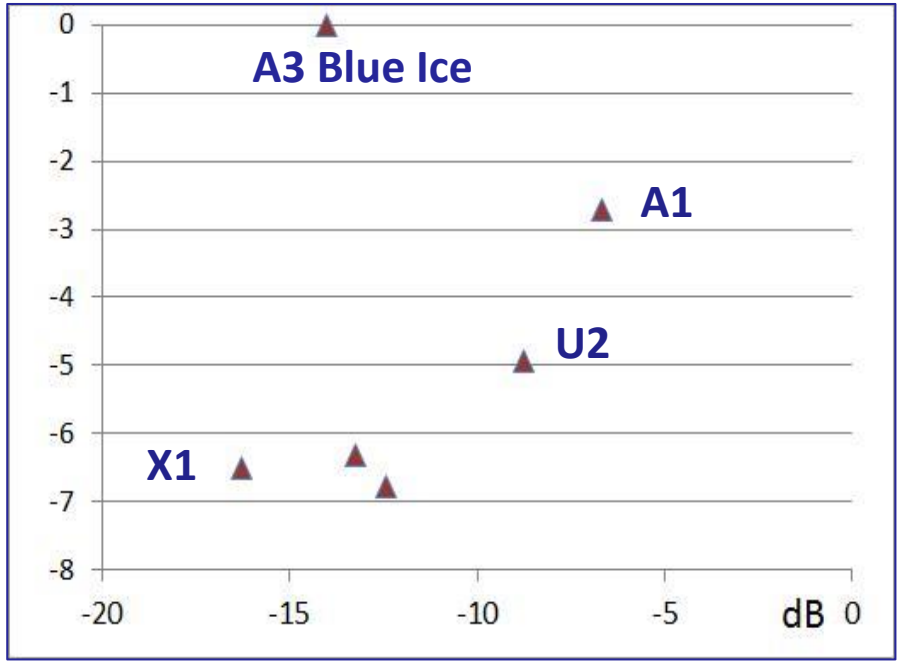
Coherence and σ°(hh) from TDM CoSSc 2013-05-06

Baseline: B_n = 127 m, H_a = 65.6 m, θ =40°

Coherence



Backscatter σ°(HH)



A1 to X1: increasing volume decorrelation

A1 to X1: decreasing scattering albedo

Coherence-based Estimate of Penetration

Coherence estimate

$$|\hat{\gamma}| = \frac{\left|\sum_W V_1(m,n)V_2^*(m,n)\right|}{\sqrt{\sum_W |V_1(m,n)|^2 \sum_W |V_2(m,n)|^2}} \; ; \; 0 \le |\hat{\gamma}| \le 1$$

Related to penetration depth

$\gamma(\text{tot}) = \gamma(\text{SNR}) \times \gamma(\text{Quant}) \times \gamma(\text{Amb}) \times \gamma(\text{RG}) \times \gamma(\text{Az}) \times \gamma(\text{volume})$

Penetration bias due to shift of InSAR phase center in volume scattering medium:

$$\Delta h_p \approx \frac{1}{2} d_l \cos\theta_r \quad for \quad \Delta h_p / |H_a| \ll 1$$ *(Dall, 2007)*

Penetration length (single layer) $d_l = 1/(\kappa_a + \kappa_s)$

κ_a = f (λ, ρ, T)

κ_s = f (λ, R_E, ρ)

Model for volume decorrelation in a lossy medium, under assumption of no depth dependence of scattering and absorption cross sections *(Hoen & Zebker, 2000)*

Inverting for penetration

$$\gamma_{vol} = 1 \Big/ \sqrt{1 + \left(\frac{2\pi \sqrt{\in}\, \boldsymbol{d_p} B_n}{R\, \lambda\, tan\theta}\right)^2}$$

Inversion of γ_{vol} with UG data results in overestimation of $\Delta h_p \Rightarrow$ dense medium effect causes decrease of κ_s below about 2 m depth $\Rightarrow$ need to account for depth dependence

The field studies and analysis of topographic satellite data show clear relations between penetration bias, firn microstructure and interferometric signatures

Further Data Analysis:

- Analysis of interferometric properties with full Union Glacier TDM data set: several HH-pol. acquisitions 2013 to 2015; HH- & VV-pol. 11-day repeat time series Nov. 2016 to Feb. 2017
- Consolidate relations between coherence, σ° and penetration at field sites and along available ICESat tracks
- Quantify impact of polarization, incidence angle, InSAR baseline and firn structure on X-band penetration bias
- Check differences between TDM and CryoSat surface elevation data for firn types with different structural properties

Model Development:

- EM forward model relating sigma-0 and coherence to structure of polar firn
- Inversion model for estimating penetration bias from interferometric and backscatter properties


Many Thanks for your Attention!